TriG - A GNSS Precise Orbit and Radio Occultation Space Receiver

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ABSTRACT

The GPS radio occultation (RO) technique [1] produces measurements in the ionosphere and neutral atmosphere [2] that contribute to monitoring space weather and climate change; and improving operational weather prediction. The high accuracy of RO soundings, traceable to SI standards, makes them ideal climate benchmark observations. For weather applications, RO observations improve the accuracy of weather forecasts by providing temperature and moisture profiles of sub-km vertical resolution, over land and ocean and in the presence of clouds.

JPL is currently flying a handful of RO instruments [3] on various satellites in Low Earth Orbit (LEO). Although these receivers have served to pioneer occultation measurements, various advances in technology and understanding of the RO technique along with availability of new signals from GPS and other GNSS satellites allow us to design an improved next generation space-based Precise Orbit Determination (POD) and RO receiver, the TriG receiver. The paper describes the architecture and implementation of the JPL TriG receiver as well as results obtained with a prototype receiver demonstrating key technologies necessary for a next-generation space science receiver.

BIOGRAPHIES

Stephan Esterhuizen completed his Masters degree in Electrical Engineering at the University of Colorado, Boulder in 2006. He received his B.S. in Electrical and Computer Engineering from the University of Colorado, Boulder in 2004. He joined JPL in 2006 where his primary task has been software and hardware development for the TOGA R&TD radio occultation and reflections instrument as well as advanced receiver design.

Garth Franklin is the group supervisor for the Advanced Radiometric Instruments and Gravity Sensing Group at NASA's Jet Propulsion Laboratory. He received his BS from Cal Poly Pomona in 1992 and has been building high precision GPS receivers for scientific applications and for precise orbit determination of low earth orbiters including Jason, Champ, Sac-C, and Grace. The Grace instruments consisted of a three antenna dual frequency GPS front end with a fully redundant digital receiver, micron level two-way microwave ranging and two integrated star cameras. For the past few years, Mr. Franklin has been the I&T manager and the BRE IAU CTM (Broad Reach Engineering Integrated Avionics unit Contract Technical Manager) for the Lisa Pathfinder mission.

Dr. Kenneth Hurst received a BA in Physics and a BA in Geology from Earlham College in 1980. He received a PhD in Geology from Columbia University in 1987. He is 80% of the way done with earning a MS in Systems Architecting and Engineering from the University of Southern California. He has worked at JPL since 1990. He has worked on precision geodetic GPS analysis, machine learning applications to science data analysis, both interplanetary and earth-focused space mission formulation, and instrument system engineering. He is currently a member of the Ionospheric and Atmospheric Remote Sensing Group.

Dr. Anthony J. Mannucci supervises the Ionospheric and Atmospheric Remote Sensing group at NASA's Jet Propulsion Laboratory. He specializes in developing and applying remote sensing systems based on Global Navigation Satellite Systems. Dr. Mannnuci leads the GPS Earth Observatory effort at JPL that produces atmospheric science data from orbiting GPS radio occultation receivers onboard the following missions: CHAMP, SAC-C, GRACE and COSMIC/FORMOSAT-3. Dr. Mannucci works on scientific interpretation of atmospheric and ionospheric remote sensing data derived from the GPS. He holds a Ph.D. in physics from UC Berkeley and has served on the WAAS Integrity Performance Panel for the Federal Aviation Administration.

Thomas Meehan received his Bachelor of Science in Electronic Engineering from California Polytechnic State University at San Luis Obispo in 1982. Mr. Meehan has worked on high precision GPS design and development JPL since 1986. He has led three major GPS instrument developments at JPL. In each of these, he contributed on both the management and technical side. Mr. Meehan has been involved at all phases of the instrument development life cycle from requirements definition to reporting the scientific results. He is currently working with scientists for the CHAMP and SAC-C spacecraft to devise improved algorithms for GPS-based occultations and reflections.

Dr. Frank Webb has 20 years experience in Earth Science, mission formulation, ground network system engineering and implementation, including programs with international partners; applied research, development and operations using precision GPS and tracking data; flight instrument development; and management of low cost tasks and projects at JPL. Currently, Dr. Webb is Deputy Section Manger at JPL for the Tracking Systems and Applications Section which is responsible for GPS based ground and space science, applications, and instruments.

Dr. Larry E. Young earned his B.A. (Physics) from the Johns

Hopkins University in 1970 and the Ph.D. (Nuclear Physics) from the State University of New York at Stony Brook in 1975. Larry has developed radiometric systems at Caltech's Jet Propulsion Laboratory since 1978, and currently supervises a group developing high precision GPS measurement systems for remote sensing from space.

I. Introduction and Motivation

JPL is developing a next-generation GNSS space science receiver, the TriG receiver. The receiver will upgrade the capabilities offered by the current state of the art BlackJack/IGOR GPS science receivers in order to meet NASA's decadal survey [4] recommendations. This includes the ability to track not only GPS, but additional GNSS signals, including Galileo, CDMA GLONASS and Compass. Most of the low level signal processing will be done inside multiple reconfigurable FPGAs, which can be updated post-launch to track new in-band GNSS signals as they become available. TriG will greatly increase the amount and quality of data by employing digital beamforming to direct multiple simultaneous high-gain beams at GNSS satellites.

With this new architecture and the availability of Galileo, GLONASS and Compass signals, many more occultations will be observed each day. The TriG receiver will have two processors, one for performing POD, and the other dedicated to occultation and other science applications. The science processor will run Linux and can be programmed by scientists in a high-level scripting language, putting the scientist in the driver's seat when it comes to onboard processing of science data.

II. Current Technology

The current BlackJack space-based GPS receiver used for Precise Orbit Determination and GPS Radio Occultations was developed by JPL. When only POD is required, a single-antenna instrument is flown, whereas when POD + RO is needed, a four antenna receiver is flown. One or two antennas are used for POD, while two other high-gain antennas are directed at the Earth's limb and another may be used for surface reflections. These higher-gain antennas improve the received signal strength of the RO signal, which is highly defocused and experiences high dynamics at the lower regions of Earth's atmosphere.

The BlackJack receiver has a total of 16 three-signal tracking channels, shared between POD and RO tracking. With a full GPS constellation of 31 satellites (August 2009), it is not uncommon to observe as many as 14 satellites with the POD antenna and multiple GNSSRO events, and with additional GNSS launches on the horizon, more than 16 tracking channels will be required.

III. Proposed Instrument

Based on JPL's previous experience with building space-science receivers, and the GPS decadal survey recommendations, four key technologies will be included in the next-generation RO receiver:

- Support for new GNSS signals, with multiple antennas using identical RF sections
- Use digital beam steering to simultaneously direct multiple high-gain beams to provide adequate SNR for tracking all frequencies at both very low (below 5 km) and very high (above 40 km) altitudes.
- Dedicated CPU for science processing
- BlackJack based real-time GNSS processing

The aforementioned technologies drive the instrument architecture. TriG will feature four main electronic sections (depicted in Figure 1):

1) GNSS Receiver (GR) - used for POD
2) RF-downconversion (RFDC) array
3) Reconfigurable Digital Processor (RDP), for low-level RO signal processing)
4) Science Processor (SP). Used for higher-level RO science processing

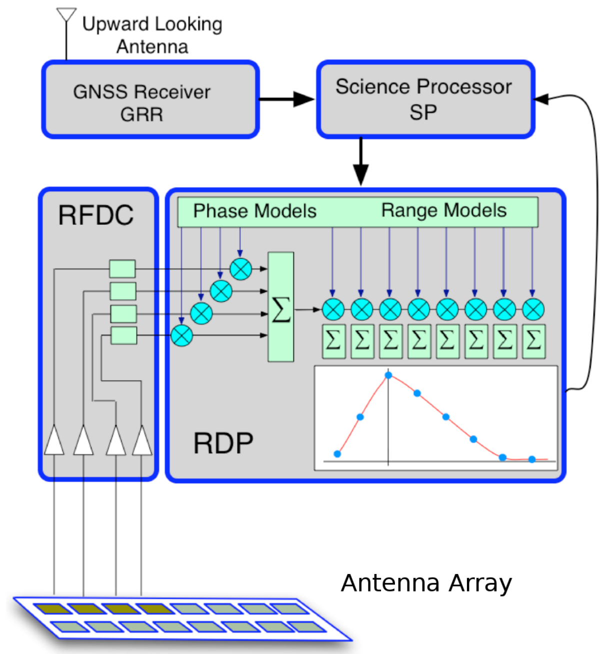

Fig. 1. High-level architecture of instrument. A GNSS Receiver provides information to the Science Processor, which computes models for the FPGA-based reconfigurable digital processor (RDP). The RDP obtains sampled data via the RF Downconverter (RFDC) board

A. RF Downconverter Array and Beamforming

A current limitation on RO observations is the required precision of measurements in the stratosphere and low signal available in the lower troposphere. Surface-reflection science requires large collecting areas to build up Signal-to-Noise Ratio (SNR). This problem can be solved by using high-gain beams to increase the received signal strength. Over the last few years JPL has developed a 16-antenna 3-frequency high-gain antenna array and downconverter prototype, and successfully demonstrated forming up to 8 simultaneous high-gain beams at 3 frequencies [5].

JPL is partnering with Broad Reach Engineering (BRE) to miniaturize this technology and build a radiation-hardened 3 frequency GNSS RF-ASIC. Multiples of these ASICS can be employed in order to support multi-element beamforming systems.

B. Reconfigurable FPGA Logic

The original BlackJack receivers had dedicated ASICs developed in the mid 1990s - this logic has since been implemented in FPGA fabric.

All the TriG computationally intensive digital signal processing will be executed on reconfigurable FPGA logic. This allows for reprogramming algorithms from the ground as needed. This reprogrammability is extremely flexible since support for new in-band GNSS signals can be added as they become available. This was demonstrated [6] with a BlackJack receiver in 2005 when L2C tracking was enabled by uploading new firmware to the instrument in-orbit.

C. Dual processors for GNSS POD and RO functions

The BlackJack/IGOR design runs on a single COTS microprocessor. All POD and RO processing is done inside this single processor. The microprocessor can track up to 11 POD satellites and 4 RO satellites simultaneously. As mentioned, this will not suffice for future missions where a plethora of satellites from multiple constellations will be visible.

The new receiver will break up the POD and RO functions into two separate processors. Both CPUs will handle higher-level signal processing, leaving dedicated reprogrammable FPGA logic to perform the high-speed signal processing. This new design will allow the TriG receiver to track 24 satellites for POD and 8 satellites for RO with digital beam steering, taking advantage of the current and planned GNSS constellation.

IV. TriG Technology Demonstration

As part of the NASA Instrument Incubator program, JPL developed a prototype [5] of the TriG receiver (TOGA) and demonstrated dual processor coupling, multi-frequency beamforming, and L5 tracking of both Galileo, GPS, and WAAS L5 signals. Below we investigate the instrument's performance, looking specifically at amplitude and phase stability as well as the new GPS L5 signals.

A. Amplitude and Phase Stability Between Channels

The stability of both amplitude and phase is important when performing beamforming. Ideally the received amplitudes should be the same for all antennas so that amplitude weighing isn't required (simplifies DSP hardware). The phase stability between RF channels is important as well, if it can be shown that these channels are stable to within a few millicycles over days, calibration can be performed less frequently, ideally only once in the instrument's lifetime.

To test amplitude and phase stability, a single tone at -110 dBm was passively split 8-ways, with 4 channels connected to the first RFDC board and the other 4 channels connected to another RFDC board. In this fashion, stability between boards and channels can be compared. The effect of a sudden temperature change was observed on the first day of the test around 17:00 by warming the RFDC boards up with a heat gun for a few seconds. The boards performed remarkably well, with relative phase varying only up to a few millicycles, while the amplitude change was nearly undetectable.

Over two and a half days the amplitude didn't vary more than a few tenths of a dB (Figure 2). The relative amplitude between channels remained well balanced, with RF channel 1 having the highest amplitude, while RF channel 6 had the lowest - both these channels were within 0.3dB.

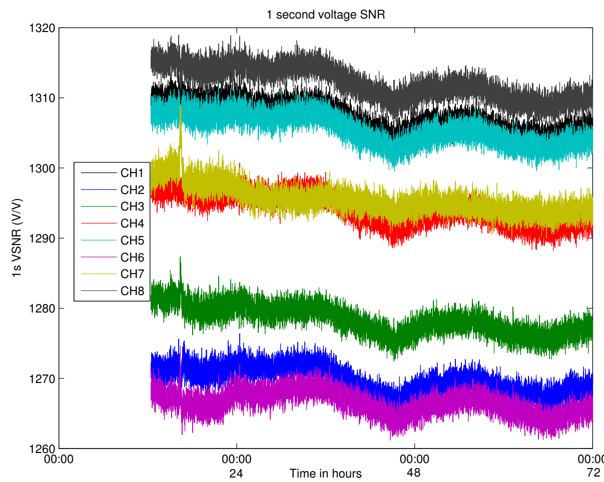

Fig. 2. Amplitude stability over 2.5 days. All channels matched amplitude to less than half a dB.

The phase stability, plotted in Figure 3 indicates the phase between channels and between RFDC boards do not vary more than a few milli-cycles over more than 2 days.

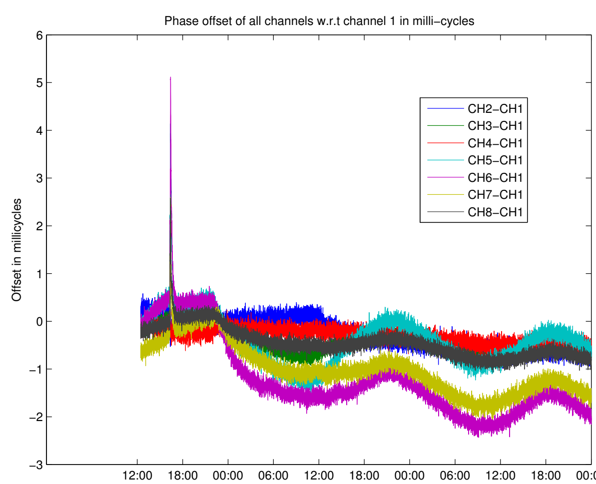

Fig. 3. Phase stability over 2.5 days. The spike at 17:00 was caused by heating the RFDC boards up with a heat gun. Overall the relative phase didn't vary more than 2 millicycles over the data collection period.

B. Arraying tests

1) Arraying with pure tone: The simplest method to test arraying is to inject a tone into the RFDC then counter-rotate and accumulate the samples. This setup is illustrated in Figure 4. Once phase calibrations and offsets due to geometry have been determined, beamforming is a very simple process. Figure 5 shows the 8 low-amplitude sinusoids, which are the outputs of the accumulation process for each individual tone. Note there is a residual doppler left on the signal, this is because the phase rate model wasn't perfect. Note also, how all 8 tones match in phase, this indicates we correctly accounted for instrumental delays and delay due to geometry. The signals can now be coherently added together resulting in an increase of SNR while preserving phase information.

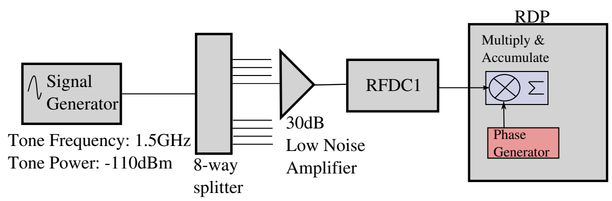

Fig. 4. Setup for beamforming test using tones. The tone was split 8 ways and then amplified by 8 individual amplifiers. This was done to create independent noise at all 8 channels. After sampling, the tones were counter-rotated with a phase model and accumulated over 1 millisecond

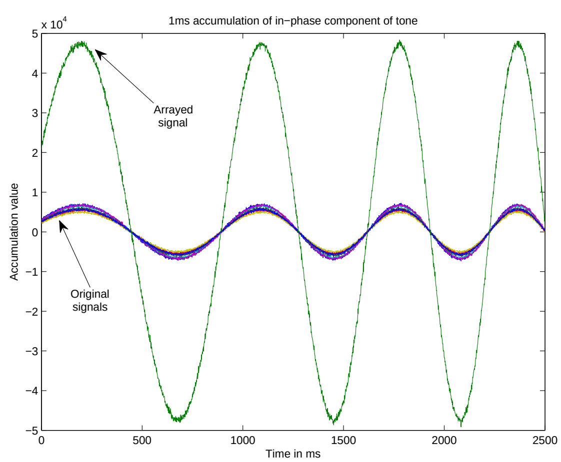

Fig. 5. This plot shows the output of the in-phase component after phase counter-rotation and accumulation. Note that all 8 signals are coherent with respect to each other, meaning our arraying is working correctly, adjusting the phase correctly for each "antenna element" to maximize SNR. After arraying, the resulting (higher amplitude) signal can be seen

2) Beamforming with GPS: Beamforming was conducted with 16 antennas observing the direct GPS signal at L1/L2/L5 frequencies. Figure 6 shows the results after 3 simultaneous L1 beams were formed and pointed at PRN1, PRN31 and PRN32. There is an obvious increase in signal amplitude, but one must carefully examine the RMS noise of the measurement, which in this case increased by a factor of 4.22, while the amplitude increased by a factor of 16 - resulting in a SNR increase of 3.8, very close to the theoretical $\sqrt{16} = 4$.

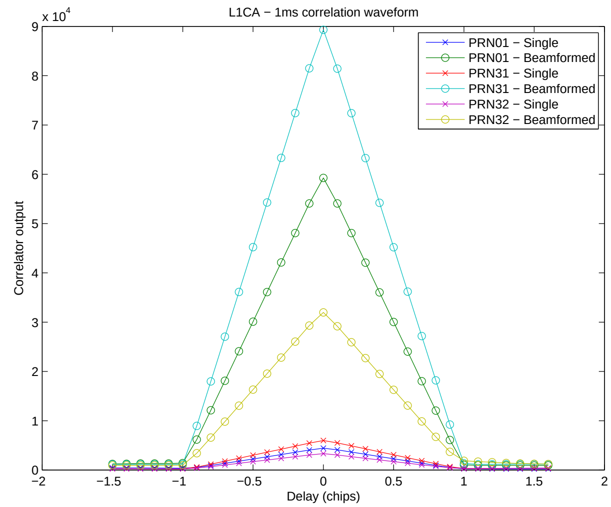

Fig. 6. RSS of correlation waveform before and after L1 beamforming. Three simultaneous beams were formed pointing at PRN1, PRN31 and PRN32 with 16 antennas. The signals were complex sampled at 20.456 MS/s

C. Added L5 capability

On 10 April 2009, SV49, started broadcasting the very first GPS L5 transmission. The TOGA receiver was connected to a high-gain 3 meter parabolic antenna and L1/L2/L5 signals were captured. Figures 7 and 8 indicate the received signal amplitude and phase respectively during the L5 first-light event.

The signal turned on approximately 70 milliseconds after GPS second 923399908.5 and took about 20 milliseconds to reach full power, while phase stabilized around 5 milliseconds after turn on.

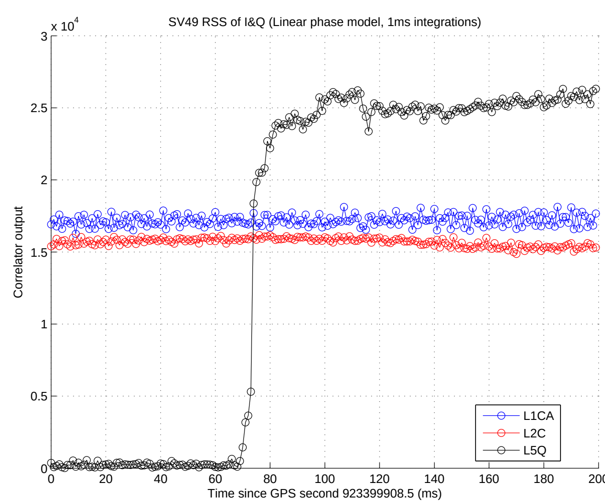

Fig. 7. SV49 L1/L2/L5 signal strength during L5 first light. Sampling rate was complex 20.456MS/s

After observation of the new L5Q signal, it became obvious that there is a glitch in L5 carrier phase every 1.5 seconds exactly aligned with the Z-epoch. Figure 9 shows L1-L5 differenced carrier phase. When multiple of these phase segments are overlayed (Figure 10) one can see the phase jumps are very repeatable. The cause of these phase jumps

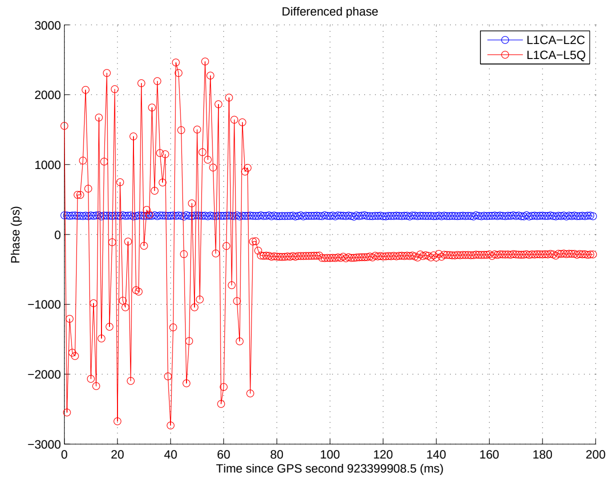

Fig. 8. SV49 L1/L2/L5 differenced phase during L5 first light

are not well understood yet, but discussions with colleagues from Aerospace Corporation and Lockheed Martin indicates this could be an issue with the way the L5 code generator on GPS SV49 is reset.

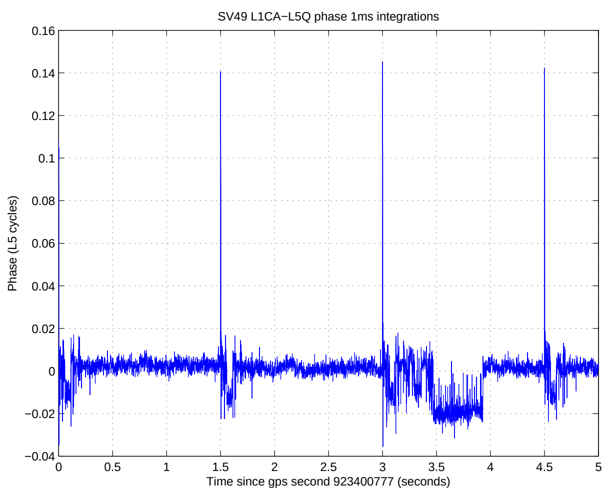

Fig. 9. SV49 L1-L5 carrier phase demonstrating anomalous phase glitches at 1.5 second intervals exactly aligned with the Z-count

V. Conclusion

An overview of JPL's proposed GNSS Precise Orbit Determination and Radio Occultation instrument, TriG, was given. This instrument will feature digital beamforming, separate POD and RO rad-hard processors, including flexible reprogrammable FPGA logic for the high-speed signal processing functions.

Many of these new features were demonstrated with a prototype receiver, TOGA, including the decoupling of POD and RO processors and steering multiple high-gain beams at GPS L1/L2/L5 as well as Galileo E1 and E5 signals.

Acknowledgements

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Special thanks to Broad Reach Engineering for their advancements to the BlackJack design with their IGOR occultation instrument and for continued development of high-reliability processors and the RF ASIC chip.

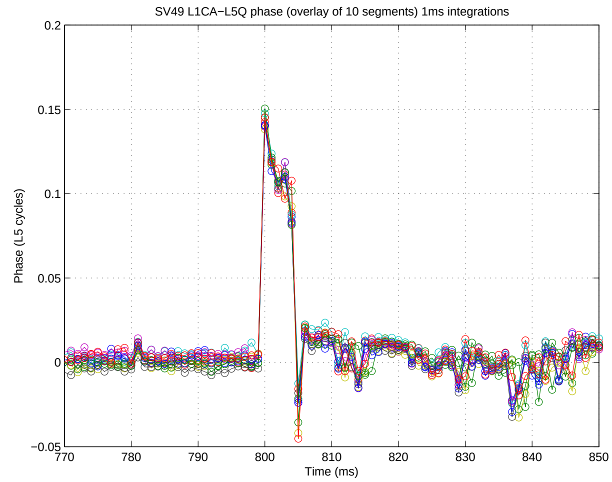

Fig. 10. SV49 L1-L5 carrier phase, multiple tracks overlay. Z-epoch occurred at 800 millisecond mark. The phase glitch is extremely well correlated over multiple Z-epoch periods

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